EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-EXO-11-099

# Search for pair produced fourth-generation up-type quarks in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ with a lepton in the final state

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## Abstract

The results of a search for the pair production of a fourth-generation up-type quark (t′) in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ are presented, using data corresponding to an integrated luminosity of about $5.0\,\text{fb}^{-1}$ collected by the Compact Muon Solenoid experiment at the LHC. The t′ quark is assumed to decay exclusively to a W boson and a b quark. Events with a single isolated electron or muon, missing transverse momentum, and at least four hadronic jets, of which at least one must be identified as a b jet, are selected. No significant excess of events over standard model expectations is observed. Upper limits for the t′t̄′ production cross section at 95% confidence level are set as a function of t′ mass, and t′-quark production for masses below 570 GeV is excluded.

*Submitted to Physics Letters B*

# 1   Introduction

The standard model (SM) of particle physics includes three generations of fermions [1–3]. However, the existence of a fourth generation is not excluded by precision electroweak data [4]. Mass scales above 550 GeV are interesting because the coupling of a fourth-generation up-type quark (referred to as $t'$ in this paper) to the Higgs field becomes large, weak interactions start to become comparable to strong interactions, and perturbative calculations begin to fail [5]. In addition, some models of physics beyond the SM [6, 7] predict the existence of top-like quarks that cancel the divergent corrections of t-quark loops to the Higgs boson mass. Such quarks give rise to the same final-state signature described below for fourth-generation $t'$ quarks.

The mass splitting between the $t'$ quark and the corresponding fourth generation down-type $b'$ quark is favoured to be smaller than the mass of the W boson [8–10]. In this case, the $t'$ quark cannot decay to $Wb'$. Assuming that the pattern of quark mixing observed in the CKM matrix extends to the fourth generation, the dominant $t'$-quark decay mode would be $t' \to Wb$, and the lifetime of the $t'$ would be short in an experimental sense.

We present the results of a search for the strong production of a $t'\bar{t}'$ quark pairs, with $t'$ decaying into $W^+b$ and $\bar{t}'$ to $W^-\bar{b}$, in proton-proton collisions at $\sqrt{s} = 7$ TeV using the Compact Muon Solenoid (CMS) detector. The search strategy requires that one of the W bosons decays to leptons ($e\nu$ or $\mu\nu$) and the other to a quark-antiquark pair. The branching fraction into this final state is about 15% for each lepton flavour. We select events with a single charged lepton, missing transverse momentum, and at least four jets with high transverse momenta ($p_T$).

Previous searches for $t'$ quarks in this final state give lower limits for the mass of the $t'$ quark of 358 GeV [11, 12] at the Tevatron and 404 GeV [13] at the Large Hadron Collider (LHC).

There are SM processes that give rise to the same signature, most notably $t\bar{t}$ and W+jets production. The present search considers a $t'$ quark with a mass larger than the SM t quark. We utilize two variables to distinguish between signal and background. The first is $H_T$, defined as the scalar sum of the transverse momenta of the lepton, the missing transverse momentum, and the four jets from the decay of the $t'$ and $\bar{t}'$ quarks. The second variable is the $t'$-quark mass $M_{fit}$, obtained from a kinematic fit of each event to the process $t'\bar{t}' \to WbW\bar{b} \to \ell\nu bq\bar{q}'\bar{b}$. We use the two-dimensional distribution of $H_T$ versus $M_{fit}$ to test for the presence of a signal for $t'\bar{t}'$ production in the data.

We categorize events according to the flavour of the lepton. Events with an identified electron (muon) are classified as e+jets ($\mu$+jets) events. The analysis procedures for the two channels are kept as similar as possible, with small differences mainly driven by the different trigger conditions. Finally, a combined statistical analysis of both channels is performed and upper limits for the $t'\bar{t}'$ pair production cross section and a lower limit on the $t'$-quark mass are derived.

# 2   CMS detector and data samples

The CMS experiment uses the following coordinate system. The $z$ axis coincides with the axis of symmetry of the detector, and is oriented in the anticlockwise proton beam direction. The $x$ axis points towards the center of the LHC ring and the $y$ axis points up. The polar angle $\theta$ is defined with respect to the positive $z$ axis, and $\phi$ is the azimuthal angle. The transverse momentum of a particle or jet is defined as its momentum times $\sin\theta$, and pseudorapidity is $\eta = -\ln[\tan(\theta/2)]$.

The characteristic feature of the CMS detector is the superconducting solenoid, 6 m in diameter

and 13 m in length, which provides an axial magnetic field of 3.8 T. Inside the solenoid are a multi-layered silicon pixel and strip tracker covering $|\eta| < 2.5$ to measure the trajectories of charged particles, an electromagnetic calorimeter (ECAL) made of lead tungstate crystals and covering $|\eta| < 3.0$, a preshower detector covering $1.65 < |\eta| < 2.6$ to measure electrons and photons, and a hadronic calorimeter (HCAL) made of brass and scintillators covering $|\eta| < 3.0$ to measure jets. Muons are identified using gas-ionization detectors embedded in the steel return yoke of the solenoid and covering $|\eta| < 2.4$. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. The CMS detector is nearly hermetic, allowing the measurement of the transverse momentum carried by undetected particles. A detailed description of the CMS detector can be found elsewhere [14].

We use data collected in 2011, corresponding to an integrated luminosity of $5.0\,\text{fb}^{-1}$ for the e+jets channel and $4.9\,\text{fb}^{-1}$ for the $\mu$+jets channel. The triggers for the e+jets data required at least one electron candidate with a $p_\text{T}$ threshold that varied between 25 and 32 GeV according to the average instantaneous luminosity. When the LHC instantaneous luminosity increased, three central jets with $p_\text{T} > 30\,\text{GeV}$ and $|\eta| < 2.6$ were also required. The triggers for the $\mu$+jets channel required at least one muon candidate with a $p_\text{T}$ threshold that varied between 30 and 40 GeV. No requirements were made on jets in the triggers for the $\mu$+jets events.

We model the $t'\bar{t}'$ signal and SM background processes using Monte Carlo (MC) simulations. The $t'\bar{t}'$ signal events are generated for $t'$ masses from 400 to 625 GeV in 25 GeV steps. The following SM background processes are simulated: $t\bar{t}$ production; single t-quark production via the tW, $s$-channel, and $t$-channel processes; single- and double-boson production (W+jets, Z+jets, WW, WZ, and ZZ). All of these processes, except the dominant $t\bar{t}$ production, are collectively referred to as electroweak (EW) background.

The single t-quark production is simulated with the POWHEG event generator [15–17]. All other processes are simulated with the MADEVENT/MADGRAPH [18] programs. The PYTHIA program [19] is then used to simulate additional radiation and the fragmentation and hadronization of the quarks and gluons into jets. The generated events are processed through the CMS detector simulation based on GEANT4 [20]. Up to 20 minimum-bias events, generated with PYTHIA, are superimposed on the hard-scattering events to simulate multiple pp interactions within the same beam crossing. The MC events are weighted to reproduce the distribution of the number of vertices per event in the data (the average number of vertices per event is 8).

The simulated samples for the $t'\bar{t}'$ signal correspond to an integrated luminosity of between 100 and $2500\,\text{fb}^{-1}$ for each value of $t'$-quark mass. Samples for the background processes giving the largest contributions correspond to $22\,\text{fb}^{-1}$ for the $t\bar{t}$ sample and $2.5\,\text{fb}^{-1}$ for W+jets.

## 3  Event reconstruction

Events are reconstructed using a particle-flow algorithm [21–23]. The particle-flow event reconstruction consists in reconstructing and identifying each single particle with an optimized combination of all subdetector information: charged tracks in the tracker and energy deposits in the ECAL and HCAL, as well as signals in the the muon system and the preshower detector. This procedure categorizes all particles into five types: muons, electrons, photons, charged and neutral hadrons. The energy calibration is performed separately for each particle type.

Electron candidates are reconstructed from clusters of energy deposited in the ECAL. The clusters are first matched to track seeds in the pixel detector. The trajectory of the electron candidate is reconstructed using a dedicated modelling of the electron energy loss. Finally, the

particle-flow algorithm further distinguishes electrons from charged pions using a multivariate approach [23].

Muon candidates are identified by reconstruction algorithms using signals in the silicon tracker and muon system. The tracker muon algorithm starts from tracks found in the tracker and then associates them with matching signals in the muon chambers. The global muon algorithm starts from standalone muons and then performs a global fit combining signals in the tracker and muon system.

Jets from the fragmentation of quarks and gluons are reconstructed from all particles found by the particle-flow algorithm using the anti-$k_T$ jet clustering method [24] with the distance parameter of $R = 0.5$, as implemented in FASTJET version 2.4 [25–27]. Small corrections [28] are applied as a function of $\eta$ and $p_T$ to the reconstructed jet energies.

A jet is identified as originating from a b quark using the combined secondary vertex (CSV) algorithm [29], which provides optimal b-tagging performance. The algorithm is based upon a likelihood test that combines information about the impact parameter significance, secondary-vertex reconstruction, and jet kinematics. The small differences in the performance of the b-tagging algorithm in data and MC simulation are accounted for by data/MC scale factors. This is done by randomly removing or adding b tags on a jet-by-jet basis, using the $p_T$- and $\eta$-dependent scale factors discussed in [29].

The missing transverse momentum in an event is defined as the negative vector sum of the transverse momenta of all objects found from the particle-flow algorithm.

The vertex with the highest sum of $p_T^2$ of all associated tracks is taken as the primary vertex of the hard collision.

## 4 Event selection, signal and background estimation

For this analysis we use an event selection similar to that adopted previously for $t\bar{t}$ events in the lepton+jets channel [30]. To reduce the background from $t\bar{t}$ production, we apply higher jet $p_T$ thresholds.

Charged leptons from W-boson decays, which are themselves originating from decays of heavy t-quark-like objects, are expected to be isolated from nearby jets. A lepton isolation variable is calculated by summing the transverse momenta of all reconstructed particle inside a cone defined as $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$, where $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle and pseudorapidity differences with respect to the lepton direction. The lepton isolation variable is equal to this sum divided by the lepton's $p_T$.

Events with exactly one isolated lepton and at least four jets with $|\eta| < 2.4$ are selected. Jets that are within a cone of $\Delta R = 0.3$ around the lepton direction are not considered. At least one jet must be identified as originating from a b quark. The thresholds for the lepton $p_T$ are driven by the trigger requirements described in Section 2. The lepton track must have an impact parameter transverse to the beam direction with respect to the primary vertex of less than 0.02 cm and along the beam direction of less than 1 cm. The missing $p_T$ in the event must be greater than 20 GeV.

The selection of the e+jets events requires exactly one electron with $p_T > 35$ GeV and $|\eta| < 2.5$, electron isolation $< 0.1$, and at least four jets with $p_T > 120, 90, 50$, and 35 GeV. The selection for the $\mu$+jets channel requires exactly one muon with $p_T > 35$ GeV or $p_T > 42$ GeV for two running periods with different trigger conditions, $|\eta| < 2.1$, muon isolation $< 0.125$, and at

least four jets with $p_T > 120, 90, 30$, and $30\,\text{GeV}$. The thresholds for the two highest-$p_T$ jets are selected to maximize the signal-to-background ratio. The thresholds for the lepton $p_T$ and the third and fourth highest-$p_T$ jets are driven by the trigger conditions.

Table 1 lists the number of observed and expected events for the various background sources after selection. The expected numbers of background events are calculated from the cross sections and integrated luminosities given in the table. The cross section for $t\bar{t}$ production is taken from a previous CMS measurement [30]. All other cross sections are computed with the MCFM program [31]. In the case of the e+jets channel, the small multijet background is estimated from data by fitting the missing-$p_T$ distribution with shapes predicted by the MC simulation. The uncertainties shown include systematic uncertainties in the efficiency and acceptance. Uncertainties are strongly correlated for all sources. Uncertainties in the cross sections and the integrated luminosity are not included.

The fraction of $t\bar{t}$ events retained by our selection is 0.7% for the $\mu$+jets channel and 0.5% for the e+jets channel.

Table 1: Background cross sections, number of events observed and background events predicted for the e+jets and $\mu$+jets samples. The predicted numbers of events are normalized to the integrated luminosity (except for the multijet events in the e+jets channel, see text).

|                        |               | e+jets | $\mu$+jets |
|------------------------|---------------|--------|------------|
| Integrated luminosity  |               | $4.98\,\text{fb}^{-1}$ | $4.90\,\text{fb}^{-1}$ |
| Background process     | Cross section | Events | Events |
| $t\bar{t}$             | $154\,\text{pb}$ | $3950 \pm 490$ | $5460 \pm 670$ |
| W+jets                 | $31\,\text{nb}$  | $462 \pm 55$   | $750 \pm 110$  |
| Single-t production    | $85\,\text{pb}$  | $208 \pm 24$   | $336 \pm 45$   |
| Z+jets, WW, WZ, ZZ     | $3.1\,\text{nb}$ | $49 \pm 8$     | $69 \pm 11$    |
| Multijets              |               | $78 \pm 9$     | $5 \pm 5$      |
| Total background       |               | $4750 \pm 560$ | $6620 \pm 800$ |
| Total observed         |               | 4734   | 6448 |

Table 2 shows the theoretical cross sections for the signal process for various $t'$-quark masses, along with the efficiencies of the event selection for the e+jets and $\mu$+jets channels and the expected numbers of signal events. The $t'\bar{t}'$ production cross sections are computed using HATHOR [32]. The efficiencies include the branching fraction of the $t'\bar{t}'$ system into a single-lepton final state, which can be obtained from the branching fractions for $W \to \ell\nu$ and $W \to q\bar{q}'$. The uncertainties quoted are the statistical uncertainties from the MC simulation.

## 5   Mass reconstruction

We perform a kinematic fit of each event to the $t'\bar{t}' \to Wb\overline{Wb} \to \ell\nu bq\bar{q}'\overline{b}$ process. There are two steps in the reconstruction of the $t'$-quark mass: the assignment of reconstructed objects to the quarks, and a kinematic fit to improve the resolution of the reconstructed mass of the $t'$-quark candidates. The four-momenta resulting from the kinematic fit of the particles in the final state must satisfy the following three constraints, where $m$ is the mass of the corresponding particles, $M_W$ is the W-boson mass, $M_{\text{fit}}$ is a free parameter in the fit (reconstructed $t'$ mass), and $\ell$ stands

Table 2: Theoretical cross sections [32], selection efficiencies, and numbers of expected events for the t′t̄′ signal with different t′ masses in the e+jets and $\mu$+jets channels. The efficiencies include the branching fraction of the t′t̄′ system into a single-lepton final state.

| $M_{t'}$ (GeV) | Cross section (pb) | e+jets eff. (%) | Events | $\nu$+jets eff. (%) | Events |
|----------|----------|----------|----------|----------|----------|
| 400 | 1.41 | $4.3 \pm 0.1$ | 302 | $5.4 \pm 0.1$ | 373 |
| 425 | 0.96 | $4.4 \pm 0.1$ | 210 | $5.6 \pm 0.1$ | 263 |
| 450 | 0.66 | $4.7 \pm 0.1$ | 155 | $6.0 \pm 0.1$ | 194 |
| 475 | 0.46 | $4.7 \pm 0.1$ | 108 | $6.1 \pm 0.1$ | 137 |
| 500 | 0.33 | $4.8 \pm 0.1$ | 79 | $6.2 \pm 0.1$ | 100 |
| 525 | 0.24 | $4.7 \pm 0.1$ | 56 | $6.4 \pm 0.1$ | 75 |
| 550 | 0.17 | $4.9 \pm 0.1$ | 41 | $6.5 \pm 0.1$ | 54 |
| 575 | 0.13 | $4.7 \pm 0.1$ | 30 | $6.6 \pm 0.1$ | 42 |
| 600 | 0.092 | $4.7 \pm 0.1$ | 22 | $6.6 \pm 0.1$ | 30 |
| 625 | 0.069 | $4.8 \pm 0.1$ | 16 | $6.5 \pm 0.1$ | 22 |

for electron or muon:

$$m(\ell\nu) = M_W, \tag{1}$$

$$m(q\bar{q}') = M_W, \tag{2}$$

$$m(\ell\nu b) = m(q\bar{q}'b) = M_{fit}. \tag{3}$$

Here $\ell$, $\nu$, b denote either particle or antiparticle.

The reconstructed objects in the event are the charged lepton, the neutrino, and four or more jets. For the neutrino, only its transverse momentum can be measured as the missing transverse momentum in the event. The $z$ component of the neutrino momentum can be determined with two solutions from the kinematic constraints. The four quarks in the final state manifest themselves as jets and their momenta are measured. Thus, all but one of the momentum components of the considered final system are measured. With one unknown and three constraints, a kinematic fit is performed by minimizing the $\chi^2$ computed from the difference between the measured momentum of each reconstructed object and its fitted value, divided by its uncertainty.

We have studied different strategies for pairing the observed jets with the four quarks from the decay of the t′ and t̄′ quarks to find the best separation between the t′t̄′ signal and the tt̄ background. In events with exactly four jets, we consider all possible jet-quark assignments. To reduce the number of combinations, we choose only those in which at least one b-tagged jet is assigned to a b quark from the t′t̄′ decay. In events with more than four jets, we take the five jets having the highest $p_T$ values, and consider all combinations of four out of these five jets. In each event, the kinematic fit is carried out for each jet-quark assignment, and the jet-quark assignment with the smallest $\chi^2$ value is chosen. This procedure selects the correct jet-quark assignment in 36–40% of the simulated t′t̄′ events over a t′-quark mass range of 400–625 GeV for all jet multiplicities together. For tt̄ events this fraction is much lower, about 19%, because the jets from the decays of the t and t̄ quarks are softer than from t′ and t̄′ decays and, therefore, are less likely to be among the five highest-$p_T$ jets in the event. The $\chi^2$ value does not distinguish the t′t̄′ signal from the tt̄ background because both processes satisfy the fit hypothesis, but using the smallest value for each event does increase the fraction of correct quark assignments. Since a restriction on $\chi^2$ does not improve the signal-to-background ratio, no such restriction is applied.

Figures 1 and 2 show the two-dimensional $H_T$ versus $M_{\text{fit}}$ distributions for the data, $t\bar{t}$ simulation, the other simulated backgrounds, and the t′t̄′ simulation with a particular t′ mass of 550 GeV in the e+jets and $\mu$+jets channels, respectively. Figure 3 shows the corresponding $M_{\text{fit}}$ and $H_T$ projections. The integrated luminosities given in Table 1 are used for the normalization of the background processes. The data are found to be in agreement with the predicted background $M_{\text{fit}}$ and $H_T$ distributions. The $t\bar{t}$ events that pass the selection criteria either have high-$p_T$ t and $\bar{t}$ quarks that produce high-$p_T$ jets in their decays or they have high-$p_T$ jets from initial-state gluon radiation. The former class of events is responsible for the relatively narrow peak in the $M_{\text{fit}}$ distribution at the t-quark mass. The $M_{\text{fit}}$ distribution of the latter class of events is broad and typically populates the region above the t-quark mass, leading to the observed high-mass tail in the $M_{\text{fit}}$ distribution.

# 6   Computation of t′t̄′ cross section limits

The two-dimensional distributions of $H_T$ versus $M_{\text{fit}}$, such as those shown in Figs. 1 and 2, are used to search for a t′t̄′ signal in the data. Simulated t′t̄′ signal distributions are produced for t′ masses from 400 to 625 GeV in 25 GeV steps. We do not use the two-dimensional histograms directly because it is not possible to simulate enough events to adequately populate all bins of the distributions for both signal and background. Therefore, we employ a new procedure that combines bins.

All the background distributions are added together to obtain the expected background event yield in each bin of the $H_T$ versus $M_{\text{fit}}$ histogram. Then the projections of the two-dimensional signal and background histograms onto the $H_T$ and $M_{\text{fit}}$ axes are separately fitted with analytic functions. Next, we compute the expected signal-to-background (s/b) ratio for each two-dimensional bin as the product of the values of the two one-dimensional-bin fit functions for the signal and for the background at the bin center. All two-dimensional bins are then sorted in increasing order of the expected s/b ratio, which we call s/b rank. Using the fit functions for calculating the s/b ordering rank removes biases due to statistical fluctuations in the simulated signal and background samples. These functions are used only to define the ordering of the bins.

We then merge the two-dimensional bins that are adjacent after ordering by s/b ratio so that the fractional statistical uncertainty of both the signal and the background predictions is below 20% in all bins. We select the 20% value as a compromise between two tendencies. Values above 20% would give better signal sensitivity, but they could lead to significant biases in the t′t̄′ cross section determination. Figure 4 shows the colour-coded maps of the merged bins obtained for the simulation of a t′ quark with a mass of 550 GeV. The colour represents the rank of the bin in the s/b ordering. A higher rank corresponds to a higher s/b value.

In Fig. 5, the number of events in the merged bins is plotted versus s/b rank. In these histograms, signal events will predominantly cluster towards the right, and background events towards the left. These one-dimensional histograms are used as input to the t′t̄′ cross section computation, and we will refer to these distributions as templates in the following. The data agree with the predicted background distributions in Fig. 5, with no evidence for a t′ signal. Thus, we use the results to set upper limits on the t′t̄′ cross section as a function of t′ mass.

The computation of the limits for the t′t̄′ cross section uses the $CL_s$ criterion [33, 34]. The first step is to perform a likelihood fit to the data. We group the background in two components: the larger one due to $t\bar{t}$ production and the smaller one from all EW processes (W+jets, Z+jets, single-t, and diboson production) and from multijet processes. Each background component is
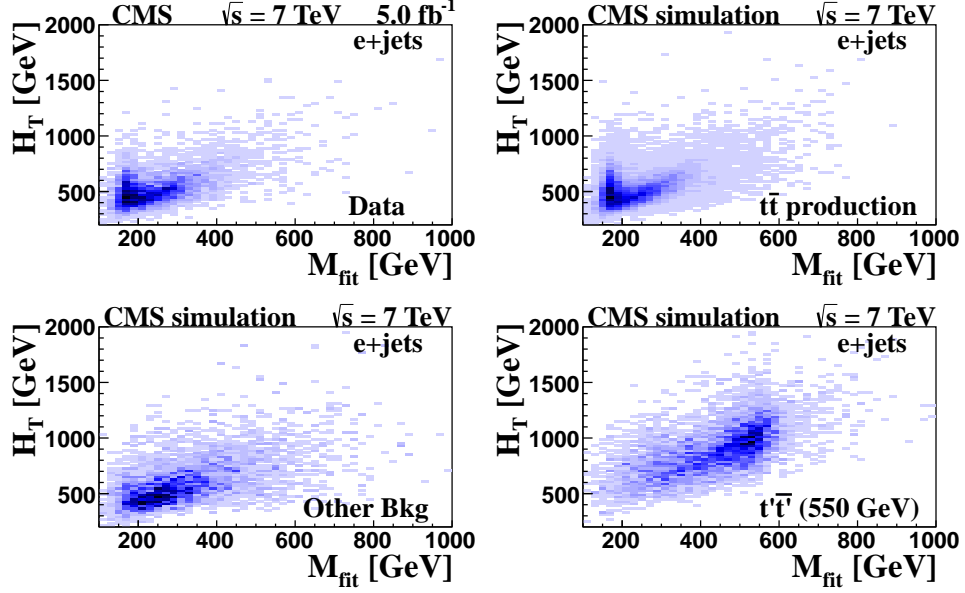
Figure 1: $H_T$ versus $M_{fit}$ for the e+jets channel from data (top left), and simulations of $t\bar{t}$ production (top right), other backgrounds (bottom left), and $t'\bar{t}'$ production (bottom right) for $M_{t'} = 550\,\text{GeV}$.
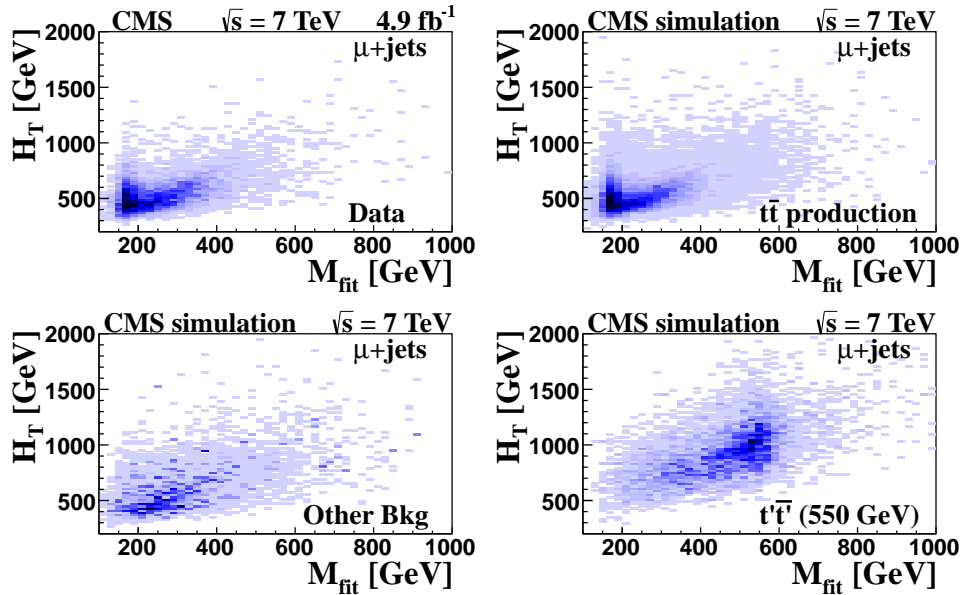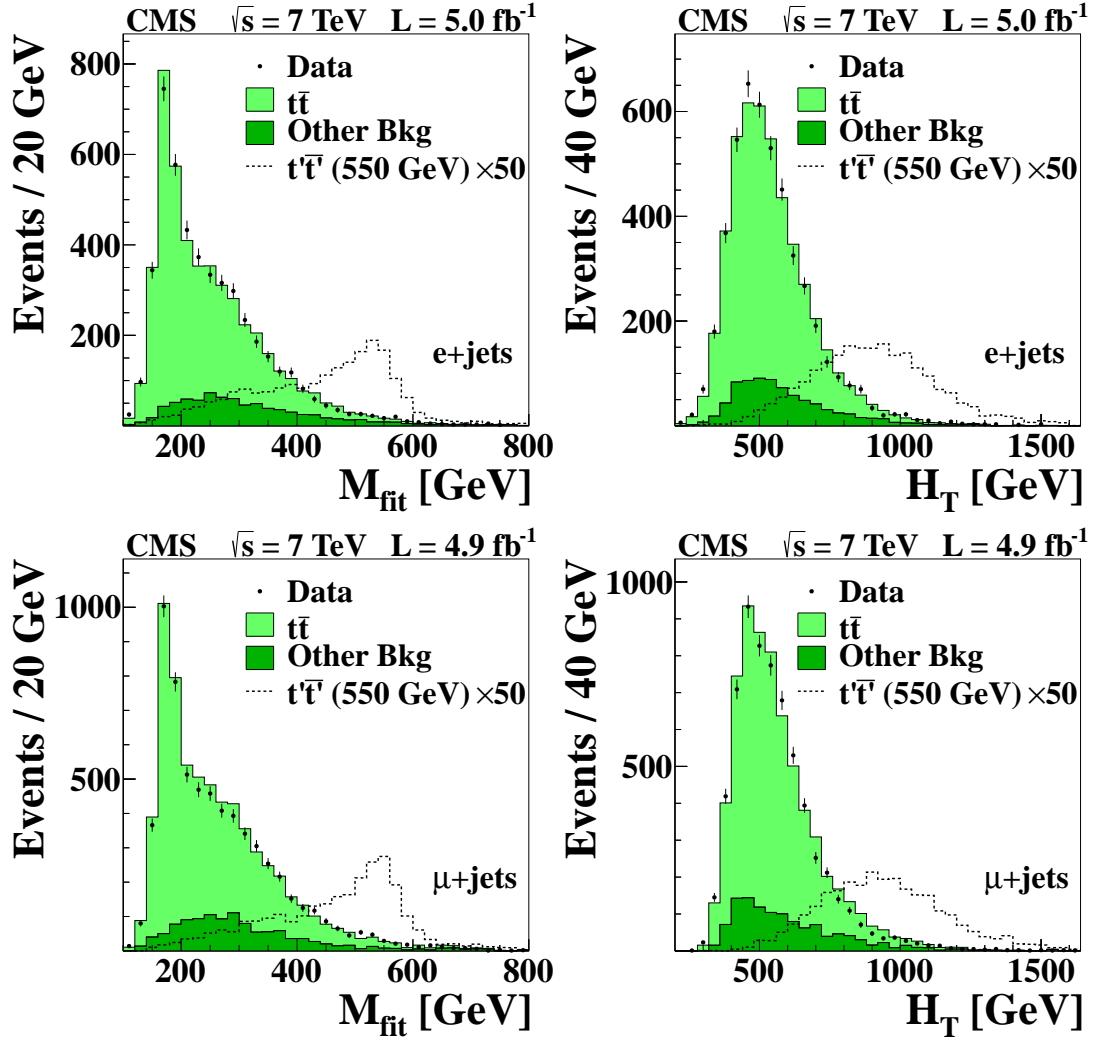


Figure 2: $H_T$ versus $M_{fit}$ for the $\mu$+jets channel from data (top left), and simulations of $t\bar{t}$ production (top right), other backgrounds (bottom left), and $t'\bar{t}'$ production (bottom right) for $M_{t'} = 550\,\text{GeV}$.

Figure 3: Distributions of $M_{fit}$ (left) and $H_T$ (right) for the e+jets (top) and $\mu$+jets (bottom) channels. The data are shown as points, the simulated backgrounds as shaded histograms, and the expected signal for a t′ mass of 550 GeV as dashed histograms (multiplied by a factor of 50 to improve visibility).
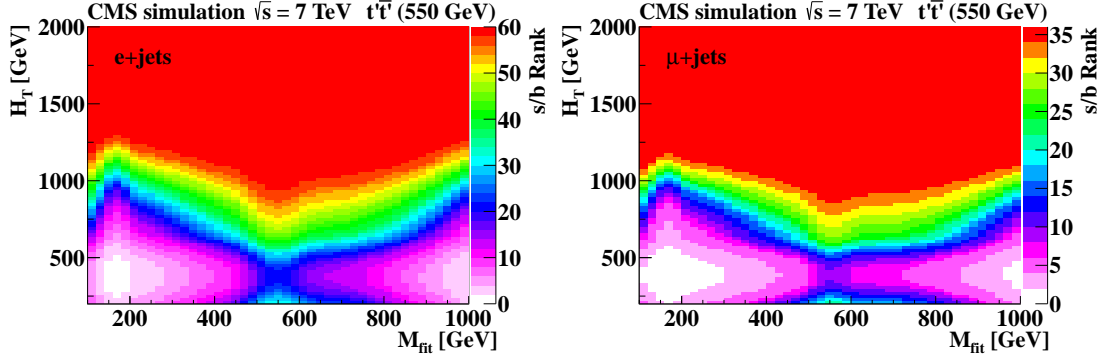
Figure 4: Map of the merged bins in the $H_T$ versus $M_{fit}$ plane for a $t'$ quark with a mass of 550 GeV for the e+jets (left) and $\mu$+jets (right) channels. The colour represents bins merged according to increasing signal-to-background (s/b) ratio. The vertical colour axis is labelled by s/b rank and corresponds to the bin index of the one-dimensional histograms of Fig. 5.
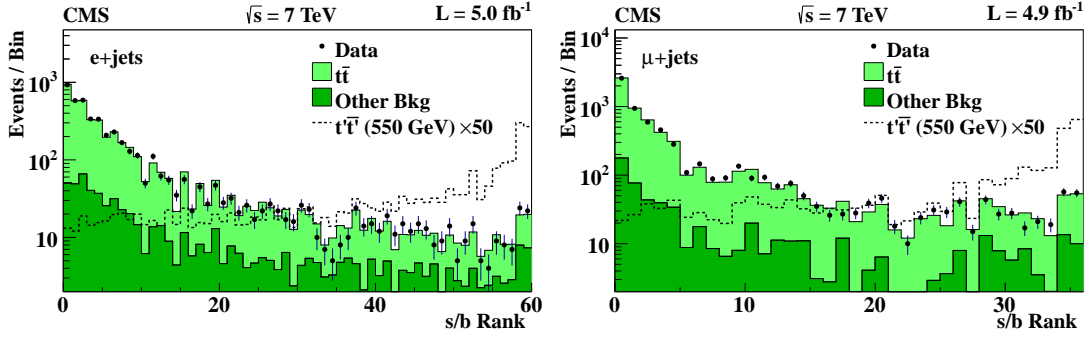


Figure 5: Number of events per bin in the two-dimensional $H_T$ versus $M_{fit}$ histogram after bin merging, as a function of the signal-to-background (s/b) rank for the e+jets (left) and $\mu$+jets (right) channels. The data are shown by the points, the simulated $t\bar{t}$ and other background distributions by the histograms, and the prediction for a $t'\bar{t}'$ signal with a $t'$ mass of 550 GeV by the dotted lines (multiplied by a factor of 50 for easier viewing).

normalized to its expected yield and multiplied with a scale factor that is a free parameter in the fit. The $t'\bar{t}'$ cross section, $\sigma$, is also a free parameter in the fit. The following likelihood ratio is used as the test statistic:

$$t(q|\sigma) = \begin{cases} L(q|\sigma, \hat{\alpha}_\sigma)/L(q|\hat{\sigma}, \hat{\alpha}) & \text{if } \sigma > \hat{\sigma} \\ 1 & \text{if } \sigma \leq \hat{\sigma}. \end{cases} \qquad (4)$$

Here, $L(q|\sigma, \alpha)$ is the likelihood of the data having the value $q$ for the parameter of interest and the nuisance parameters $\alpha$. The nuisance parameters account for effects that give rise to systematic uncertainties in the templates and include the normalizations of the background components. The likelihood reaches its maximum when $\sigma = \hat{\sigma}$ and $\alpha = \hat{\alpha}$. The symbol $\hat{\alpha}_\sigma$ refers to the values of the nuisance parameters $\alpha$ that maximize the conditional likelihood at a given value of $\sigma$.

Using the asymptotic approximation for the test statistic described in [35], the probability to observe a value $t$ for the likelihood ratio that is larger than the observed value $t_{obs}$ is determined. This is done by producing samples of "pseudo-experiments" in which the expected numbers of

signal and background events are allowed to vary according to their statistical and systematic uncertainties. For the pseudo-experiments generated with background only, this probability is denoted by $CL_b$. For pseudo-experiments with a cross section $\sigma$ for the $t'\bar{t}'$ signal, this probability is denoted by $CL_{s+b}(\sigma)$, which is a function of $\sigma$. The upper limit at the 95% confidence level ($CL$) for the $t'\bar{t}'$ cross section is the value of $\sigma$ for which $CL_s = CL_{s+b}/CL_b = 0.05$. To determine the limits for both lepton channels combined, we simultaneously fit the histograms from both channels, accounting for correlations among the nuisance parameters, and then apply the $CL_s$ method described above.

# 7 Systematic uncertainties

The signal and background predictions are subject to systematic uncertainties. Below, we describe all sources of systematic uncertainties that have been considered. They can be divided into two categories: uncertainties that only impact the normalization of the signal and background templates, and uncertainties that also affect the shape of the distributions.

The uncertainties in the $t\bar{t}$ cross section, electroweak and multijet background normalizations, integrated luminosity, lepton efficiencies, and data/MC scale factors affect only the normalization.

The uncertainty on the cross section for $t\bar{t}$ production is taken from the CMS measurement of $154 \pm 18$ pb at $\sqrt{s} = 7$ TeV [30]. The predicted yields of the EW and multijet backgrounds are determined as described in Section 4. A 50% uncertainty is assigned to the sum of these two backgrounds in the likelihood fit to the data in order to account for the uncertainty in the acceptance and the W+jets normalization.

The integrated luminosity affects the normalization of the $t'\bar{t}'$ signal and the background templates in a correlated way. The integrated luminosity is known to a precision of 2.2% [36].

Trigger efficiencies, lepton identification efficiencies, and data/MC scale factors are obtained from data using decays of Z bosons to dileptons. Their uncertainties are included in the selection efficiency uncertainty. They amount to 2% for the $\mu$+jets channel and 3% for the e+jets channel.

Uncertainties that affect the shape of the distributions include those on the jet energy scale, jet energy resolution, missing-$p_T$ resolution, b-tagging efficiency, number of multiple pp interactions, factorization/renormalization scale $Q$, matrix-element/parton-shower matching threshold [37], and initial- and final-state radiation. To model these uncertainties, we produce additional templates by varying the nuisance parameter that characterizes the systematic effect by $\pm 1$ standard deviation. To determine the signal and background templates used in the fit for any value of the nuisance parameter, we interpolate the content of each bin between the varied and nominal templates. This procedure is often referred to as vertical morphing.

The energy of all jets is obtained using the standard CMS jet energy calibration constants [28]. The sum of the four-momenta of the jets is 100% correlated with the measured missing $p_T$. The jet energy scale uncertainty affects the normalization and the shape of the $H_T$ vs. $M_{fit}$ distribution. This is taken into account by generating $H_T$ vs. $M_{fit}$ distributions for values of the jet energy scaled by $\pm 1$ standard deviation of the $\eta$- and $p_T$-dependent uncertainties from [28].

The energy resolution of jets in the simulation is better than in the data. Therefore, random noise is added to the jet energies in the simulation to worsen the resolution by 10%, to match the actual resolution of the detector. To estimate the corresponding uncertainty, the analysis

is performed without smearing and with 20% smearing. The missing-$p_T$ resolution is also simultaneously corrected for this effect.

The systematic uncertainty from the b-tagging efficiency is estimated by varying this efficiency by $\pm1$ standard deviation taken from [29].

To evaluate the uncertainties related to the modelling of multiple interactions in the same beam crossing, the average number of interactions in the simulation is varied by $\pm8\%$ relative to the nominal value.

The uncertainty in the factorization/normalization scale $Q$, used for the strong coupling constant $\alpha_s(Q^2)$, is estimated by using two sets of simulated $t\bar{t}$ samples in which the $Q$ value is increased and decreased by factors of two relative to the nominal value.

The uncertainty arising from the threshold for matching between matrix elements and parton showers [37] is estimated using two simulated $t\bar{t}$ samples generated with the matching threshold varied up and down by a factor of two from the default value.

The impact of initial- and final-state radiation is estimated using a $t\bar{t}$ MC sample generated with POWHEG, instead of MADEVENT/MADGRAPH.

We estimate the effects of these systematic uncertainties on the expected $t'\bar{t}'$ cross section limits by adding them to the limit calculation one at a time. The largest effects on the expected limits come from the normalizations of the EW background, the jet energy scale calibration, and the normalization of the $t\bar{t}$ background. All other uncertainties change the expected limits by insignificant amounts. In order to simplify the computational complexity of the limit computation, we therefore consider only a limited set of systematic uncertainties in the limit calculation by assigning nuisance parameters to them: the integrated luminosity, normalization of the EW and $t\bar{t}$ backgrounds, lepton efficiency, jet energy scale, and parton-shower matching threshold. The additional effect of the other uncertainties is negligible. All of these except the lepton efficiency are treated as correlated in the combined result from the e+jets and the $\mu$+jets channels.

## 8 Results

Figure 6 shows the observed and expected 95% $CL$ upper limits on the $t'\bar{t}'$ cross section for the e+jets (top), the $\mu$+jets (middle) channels, and the combination of both channels (bottom). The 95% $CL$ lower limit for the $t'$-quark mass is given by the value at which the observed upper limit curve for the $t'\bar{t}'$ cross section intersects the theoretical curve, also shown in Fig. 6. In the e+jets channel this happens for the 95% $CL$ observed (expected) lower limits for a $t'$-quark mass of 490 (540) GeV. In the $\mu$+jets channel the corresponding $t'$-quark mass limit is 560 (550) GeV. The combined observed (expected) limit from both channels is 570 (590) GeV. A comparable upper limit on the $t'$ mass of 557 GeV was obtained recently by the CMS Collaboration using a dilepton channel [38].

## 9 Summary

The results of a search for up-type fourth-generation quarks that are pair produced in pp interactions at $\sqrt{s}$ = 7 TeV and decay exclusively to Wb have been presented. Events were selected in which one of the W bosons decays to leptons and the other to a quark-antiquark pair. The selection required an electron or a muon, significant missing transverse momentum, and at least four jets, of which at least one was identified as a b jet. A kinematic fit assuming $t'\bar{t}'$ production was performed and for every event a candidate $t'$-quark mass and the sum over the
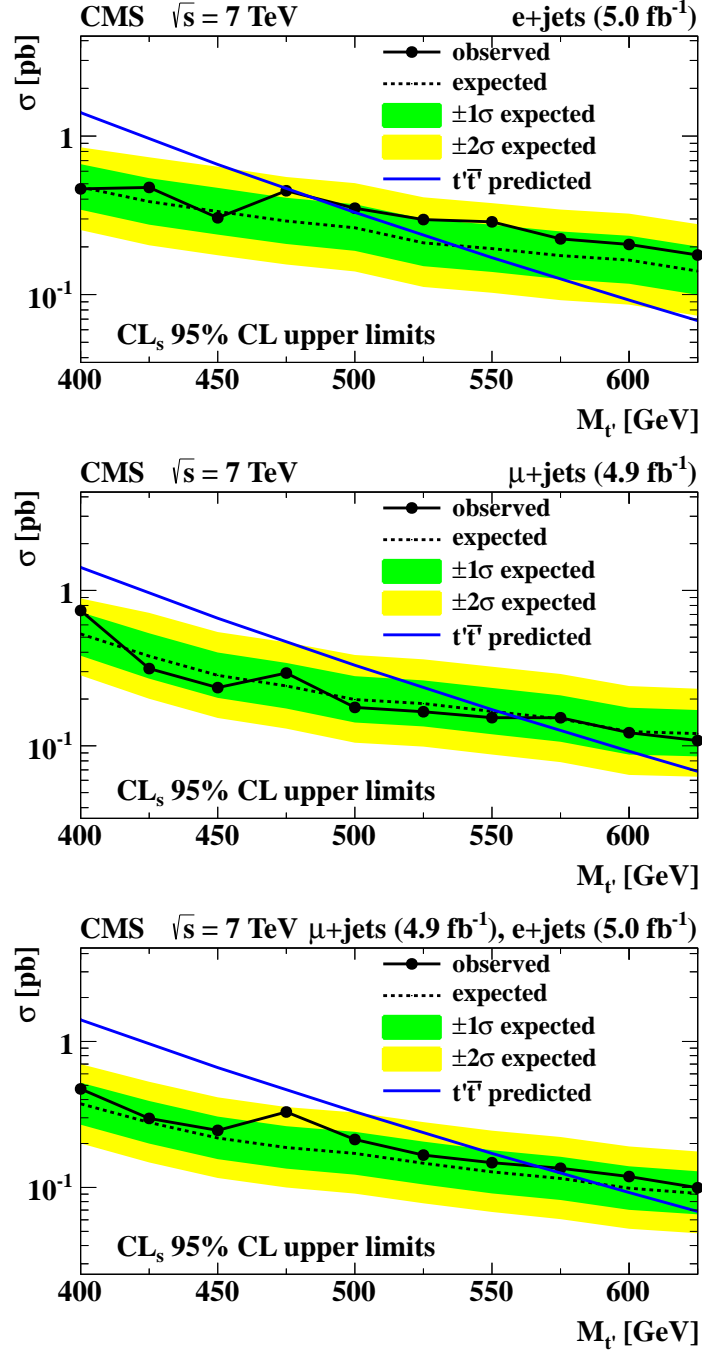
Figure 6: The observed (solid line with points) and expected (dotted line) 95% *CL* upper limits on the t′t̄′ production cross section as a function of the t′-quark mass for e+jets (top), μ+jets (middle), and combined (bottom) channels. The ±1 and ±2 standard deviation ranges for the expected limits are shown by the bands. The theoretical t′t̄′ cross section is shown by the continuous line without points.

transverse momenta of all decay products of the $t'\bar{t}'$ system were reconstructed. No significant deviations from the Standard Model expectations have been found in these two-dimensional distributions, and upper limits have been set on the production cross section of such $t'$ quarks as a function of their mass. By comparing with the predicted cross section for $t'\bar{t}'$ production, the strong pair production of $t'$ quarks is excluded at 95% *CL* for masses below 570 GeV under the model assumptions used in this analysis. This result and the one from [38] are the most restrictive yet found and raise the lower limit on the mass of a $t'$ quark to a region where perturbative calculations for the weak interactions start to fail and nonperturbative effects become significant.

## Acknowledgements

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